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EFFECT OF SIZE OF HANDWHEELS ON EFFORT REQUIRED FOR ROTATION

A Thesis
Submitted to the Faculty
of
Purdue University
by
Joao Botelho Machado
In Partial Fulfillment of the
Requirements for the Degree
of
Master of Science
in
Industrial Engineering
May, 1952

Thesis
M189

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The experimenter wishes to record his indebtedness to Professor W. J. Richardson for his guidance, and to Professor P. E. Irick for his assistance in the statistical analysis. He also wishes to thank the seven subjects who took part in the experiment, and his wife, Mirian, for her help in the long and tedious phase of computation of the slopes.

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ABSTRACT

Good manual controls design is one of the primary means of improving the efficiency of machine operators. One of the most important factors to be considered in the establishment of a basis for an objective comparison of different designs is the physical demand made by each upon the worker.

The purpose of this experiment was to determine some of the factors making for minimum human effort requirements in the operation of a particular type of control -- the handwheel.

To carry out the study, a task was established and an experimental work station built which permitted an operator to turn handwheels overcoming pre-adjusted resisting torques.

Quantitative data on effort expenditure rates was obtained through the use of a Sanborn EIS Metabolism Tester.

The task consisted of the operator turning the handwheels, using both hands, at a metronome-controlled tempo. The variables introduced were: (1) size of the handwheel, and (2) work load, i.e., resisting frictional torque. Sizes ranging from 4 to 14 inches (diameter) were used.

The results of the investigation, in which seven subjects were tested, disclosed that to overcome torques in

the range investigated (10 to 60 inch-pounds), using the method specified, the larger handwheels are more effective. For the torque range between 30 and 60 inch-pounds, little effort is saved by using diameters higher than 10 inches. For torques in excess of 45 inch-pounds, handwheels of smaller diameters than 7 inches are undesirable, and for torques below that level the minimum limit is at 5 inches.

A secondary purpose of this experiment was to investigate the suitability of using the Sanborn EIS Metabolism Tester for studies involving relatively high levels of energy expenditure. The results demonstrated its usefulness under these conditions.

EFFECT OF SIZE OF HANDWHEELS ON EFFORT REQUIRED FOR ROTATION

INTRODUCTION

Almost every industrial engineer is aware of the necessity of better designs of manual controls. Although improved machinery, in general, has succeeded in reducing direct operating cost, it is not uncommon to find new machines, mechanically perfect, in which efficient operation is handicapped by unsuitable control devices. Attention has thus far been focused largely on the design of the machine itself, consideration of the system operator-machine being, usually, overlooked. As a consequence, the basic linkages of the system -- the control devices -- do not match the human requirements. This situation is, in part, justifiable in view of the absence of organized data on the subject. The issue is by no means a new one. As far back as 1926, the problem was presented for consideration of directly concerned organizations[1]. But the main questions still remain unanswered. Attempts to solve the problem have been rare, and the resulting information is sparse, and besides some studies done during the last war and aimed

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1. Weston, H. C. and Legros, I. A., "On the Design of Machinery in Relation to the Operator", Industrial Fatigue Research Board, Report 36, London, 1926.

toward specific applications[2,3], it consists of a few articles lost among the pages of technical magazines[4,5]. In these experiments, the minimum time was used, almost invariably, as the optimizing criterion (one investigator based his results on the expressed preference of the operators). In spite of the fact that, for manual work, least time and least effort are often synonymous, it might happen, for a particular situation, that use of the criterion of minimum time will constitute a further disregard of human characteristics. It must be pointed out that at least some of these experiments involved short duration tasks, perhaps offering an opportunity for over-exertion, without noticeable fatigue. If we define an easy operation as one that the normal worker can do steadily for relatively long periods, it seems that minimum physical demand would be a much better criterion.

Among the control devices the popularity of the handwheels is unquestionable. Handwheels are almost always

---

[2] "Psychological Research on Equipment Design", Report No. 19, Army Air Forces, Aviation Psychology Research Reports, Edited by Paul M. Fitts, U.S. Government Printing Office, 1947.

[3] "Factors Determining Accuracy of Tracking by Means of Handwheel Controls", Foxboro Co. to Division 7 National Defense Research Committee, O.S.R.D. Reports 3451 to 3455.

[4] Raines, A. and Rosenbloom, J. H., "Ideal Torques for Handwheels and Knobs", Machine Design, August, 1948.

[5] Davis, L.E., "Human Factors in Design of Manual Machine Controls", Mechanical Engineering, October, 1949, and "Selecting Manual Controls", Machine Design, November, 1951.

present wherever a man-controlled motion of a piece of machinery is required. The present investigation is concerned with the human effort required to operate such handwheels under certain conditions.

Factors such as size, height, angle of position, required speed of rotation, torque load, etc., have an influence on the expenditure of energy of the person operating the handwheel. In this experiment the variables introduced were: (1) size of the handwheel and (2) torque load. The other controllable factors were held constant.

Beginning with the work done by Tilles[6], demonstrating that a standard medical metabolism tester could successfully discriminate between small changes in human energy output, a series of experiments using the metabolator followed. The research covering a variety of subjects; thus, this equipment was used in the determination of optimum work area angles, in the evaluation of differences on one-handed versus two-handed work, in the determination of time allowances, etc.

Although this technique is still in the experimental phase, the quality of the results obtained in this

[6] Tilles, S., "An Investigation of the Suitability of the Sanborn EIS Metabolism Tester to Basic Motion Study Experimentation", Master of Science Thesis, Purdue University, Lafayette, Indiana, 1949.

previous work leads to the choice of the Sanborn metabolator as the effort measuring device.

PURPOSE

The primary purpose of this investigation was to appraise through the use of a metabolism tester the effect of size of handwheels on the muscular effort required for rotation in overcoming different torques.

A secondary purpose was to investigate the suitability of the Sanborn EIS Metabolism Tester to experiments involving the measurement of relatively high rates of oxygen consumption.

PROCEDURE

The experiment was conducted at the Metabolic Section of the Motion and Time Laboratory, using the Sanborn EIS Metabolism Tester.

To carry out the purpose of the study, a task was established and an experimental work station built which permitted an operator to turn handwheels overcoming pre-adjusted resisting torques (Figure 1).

The determination of the number of subjects was governed by the time available for running and calculating the experiment. It was decided that eight operators would be used. One of the operators was unable to complete the runs. The operators were male college students having no visible injuries in their hands or arms. No attempt was made to select subjects of a given range of size or age. Data on operators' heights, ages, weights and elbow heights appear in Table 1. Each subject reported for five one-hour sessions on different days. No attempt was made to regulate the outside activity of the subjects during the period in which they took part in the experiment. The schedule of test sessions is shown in Table 2.

During each session, the subjects were tested on the Sanborn metabolator six separate times, once under the no-work condition -- basal -- and the other five while performing the task. Only the subject and the experimenter

were present at the test room. This care was taken to avoid distracting influences which might have affected the metabolic rate of the subject.

Before the experiment, each operator was given a short explanation of the purpose of the test, the nature of the equipment and detailed instructions about the task to be performed.

This task consisted of the turning of the handwheels by the subject, in the standing position facing the handwheel. The wheel rim was grasped with both hands at the ends of the vertical diameter, the right hand at the top (Figure 2). A 180° clockwise motion was impressed, and the wheel released at points diametrically opposed to the initial grasping position. The hands were then positioned for the next grasp, following the rim counter-clockwise without touching it. The cycle was then repeated. The tempo for the motions was given by a metronome, set at sixty beats per minute. The pattern was: first beat — grasp and turn; second beat — release and position.

The distance from the operator to the handwheel was such that, with the arms extended to the front, the finger tips reach approximately 12 inches beyond the handwheel.

The shaft of the handwheel was approximately in the same plane as the operator's body center line.

Based on Behl's work[7], from which he concluded that for a simple task the energy expenditure rises rapidly during the first minute of performance and does not change significantly for the next 64 minutes, a three-minute period was established for the task, the oxygen consumption being recorded during the last two minutes. According to Behl, his results would also indicate that rest periods need not be used once the experiment has commenced, if all readings can be obtained within one hour. This reason contributed to the decision of limiting the duration of the sessions to one hour.

In order to bring the subject's gaseous exchanges to a lower and more stable level, they were required to lie on a cot and have a short rest at the beginning of the session.

For all sessions, the procedure was the one shown in Table 3.

It was decided, after an examination of several machine handles manufacturers' catalogues, to test only handwheels of sizes ranging from 4" to 14". Accordingly, the following five standard sizes were selected: 4", 5", 7", 10" and 14".

[7] Behl, J. H., "Determination of the Effect of Performing a Simple Task Over a Prolonged Period on the Rate of Energy Expenditure", Master of Science Thesis, Purdue University, Lafayette, Indiana, 1951

Data on weights of the handwheels is found in Table 4.

Considering the time-consuming nature of the experiment, only five resisting torques were used; namely, 10, 15, 30, 45 and 60 inch-pound.

For reasons of simplicity, the torques and handwheels were numbered from one to five, in the order of increasing torque values and diameters, respectively. The combination of torques and handwheels gave twenty-five different testing conditions. The value chosen for the maximum torque (60 inch-pounds) is such as to make all testing conditions feasible.

These twenty-five conditions were distributed among the five sessions in which each operator's schedule was divided. According to Thorson[8], there are no significant differences in oxygen consumption rates between identical runs made on different days; his conclusions would also seem to indicate that consistent differences should be expected from runs, under different conditions, performed on different days. Based on these reasons the five-session schedule was adopted.

To avoid any adverse effect due to the order in which these conditions were presented, the order of presentation, for each subject, was randomized. This

[8] Thorson, F. J., "A Metabolic Investigation of One-Handed Versus Two-Handed Work", Master of Science Thesis, Purdue University, Lafayette, Indiana, August, 1951.

randomization was secured by the use of the Tables of Random Numbers of Kendall and Smith[9]. The order of presentation of the testing conditions appears in Table 5. In this table, the conditions are numbered in the following way: the first digit represents the torque, and the second represents the handwheel.

In addition to the Sanborn EIS Metabolism Tester (Figure 3), the equipment of the work station consisted of: (a) the handwheel shaft supported 44" above the floor by two bronze bearings fastened to a wood frame. The resisting torque offered by the shaft was obtained by a friction brake arrangement, composed of: a brake drum, a wood cylinder mounted in the shaft, a nylon band applied to the rim of the brake drum, two spring scales attached to the ends of the nylon band, and two turnbuckles attaching the top ends of the spring scales to the frame, and permitting the variation of the tension of the band, and, therefore, the friction between the brake band and the brake drum (Figure 1).

(b) A standard metronome.

(c) The set of five handwheels (Figure 4).

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9. Arkin, H., and Colton, R. R., "Tables for Statisticians", Barnes & Noble, Inc., New York, 1950, pp. 142-145.

Table 1

HEIGHTS, WEIGHTS, AGES, AND ELBOW HEIGHTS OF SUBJECTS

No.	Subject	Height	Weight	Age	Elbow Height
1	Dix, J.	6'1"	210	24	3'9"
2	Doolittle, R. H.	5'11"	165	35	3'6¼"
3	Geis, A. J.	5'10"	160	20	3'7¼"
4	Griffith, T. H.	5'7½"	163	26	3'7"
5	Markoe, K. M.	6'0"	175	20	3'8½"
6	Surver, R. L.	5'8"	185	24	3'6¼"
7	Refsum, H.	6'2"	190	24	3'10⅛"

Table 2

SCHEDULE OF TEST SESSIONS

	March															April				
Time	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5
A.M.																				
8-9	4							4	7	4	7	4	7				4	7		7
9-10				1					1		1					1		1		
10-11		3							3											3
11-12		5	3	5			5			3	5		5							
P.M.																				
6-7		8		8				6			6									
7-8	2	2		2	2	2														
8-9	6	6		6																

No.	
1	Dix
2	Doolittle
3	Geis
4	Griffith
5	Markoe
6	Surver
7	Refsum
8	Dorin (Reported to 2 sessions only)

Table 3

PROCEDURE FOLLOWED DURING THE SESSIONS

Time	Elapsed Time	Action
0-10	10	Operator relaxing quietly on a cot. Just prior to the end of the period, the operator got up and took position at the work area. The mouth piece and nose clamp were adjusted in position.
10-11	1	Operator inactive, breathing ambient air through the metabolator.
11-15	4	Without knowledge of operator, the oxygen was turned on and a basal rate was recorded.
15-20	5	Operator disconnected from equipment and resting; prior to the end of this period he was again connected to the equipment. During this resting period the metabolator was re-charged, the handwheel was changed and the torque adjusted.
20-23	3	Operator performed the first run, breathing ambient air during the first minute and oxygen during the last two minutes. The oxygen consumption was recorded.
23-28	5	Resting period, same as 15-20 minutes.
28-31	3	Second run, same as 20-23 minutes.
31-36	5	Resting period.
36-39	3	Third run.
39-44	5	Resting period.
44-47	3	Fourth run.
47-52	5	Resting period.
52-55	3	Fifth run.

Table 4

HANDWHEEL SIZES

No.	Nominal Diameter	Weight
1	4"	1.5 lbs.
2	5"	2.0 lbs.
3	7"	4.7 lbs.
4	10"	10.0 lbs.
5	14"	21.5 lbs.

Table 5

ORDER OF PRESENTATION OF THE COMBINATIONS OF TORQUES AND HANDWHEELS

Operators

1	2	3	4	5	6	7
2-5	5-4	5-3	2-1	1-1	3-2	4-1
5-1	2-5	1-1	1-2	1-3	3-3	1-3
1-2	2-4	5-5	1-4	3-2	4-2	4-3
5-5	1-2	3-1	2-5	2-2	4-3	3-5
1-5	4-5	2-2	5-5	2-3	1-2	2-5
2-4	1-1	4-2	1-3	2-4	1-1	3-1
3-1	3-2	1-2	3-1	2-5	1-4	4-4
5-2	4-2	2-5	5-4	1-3	2-1	2-3
3-5	5-2	4-1	3-3	4-2	3-4	5-5
1-3	2-2	5-2	2-4	5-3	5-3	3-4
4-4	4-4	5-1	4-1	4-4	2-4	3-3
1-4	1-3	2-4	2-3	1-5	1-3	3-2
4-2	1-5	2-3	3-5	3-4	1-5	1-4
3-4	4-3	1-4	4-3	4-1	4-5	5-4
1-1	5-5	3-5	5-3	3-3	2-2	4-5
4-3	2-3	2-1	2-2	5-5	5-4	1-5
5-3	4-1	3-3	5-1	3-5	3-5	1-2
2-1	3-5	1-3	4-4	3-2	3-1	2-2
4-5	3-1	5-4	3-4	5-4	5-5	1-1
4-1	3-3	3-4	4-2	5-2	2-3	5-1
5-4	2-1	1-5	1-1	2-1	2-5	2-4
3-2	5-3	4-5	5-2	1-2	5-2	2-1
2-2	5-1	4-4	1-5	3-1	5-1	5-2
2-3	3-4	3-2	4-5	4-3	4-1	4-2
3-3	1-4	4-3	3-2	5-1	4-4	5-3

NOTE: The first number represents the torque; and the second the handwheel.

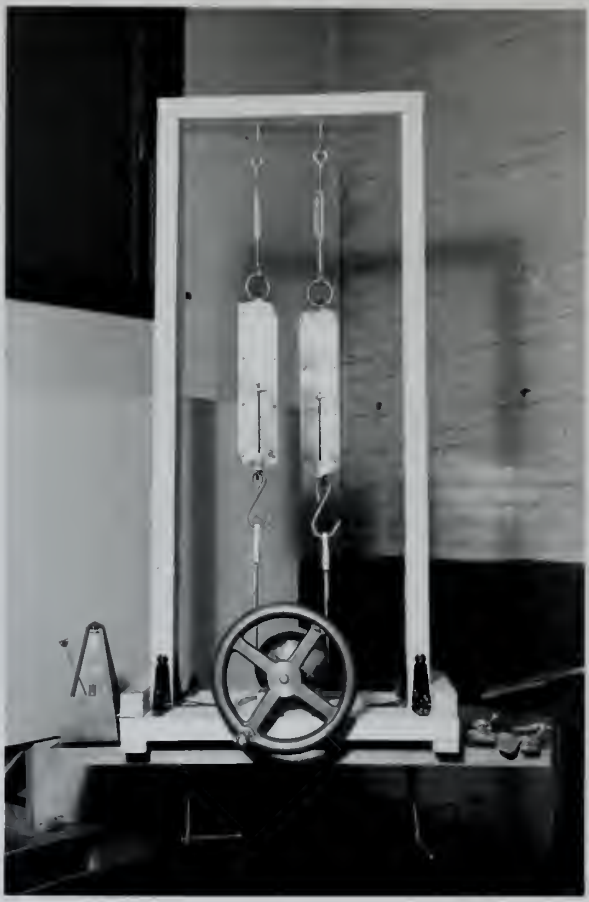

Figure 1

Experimental Work Station

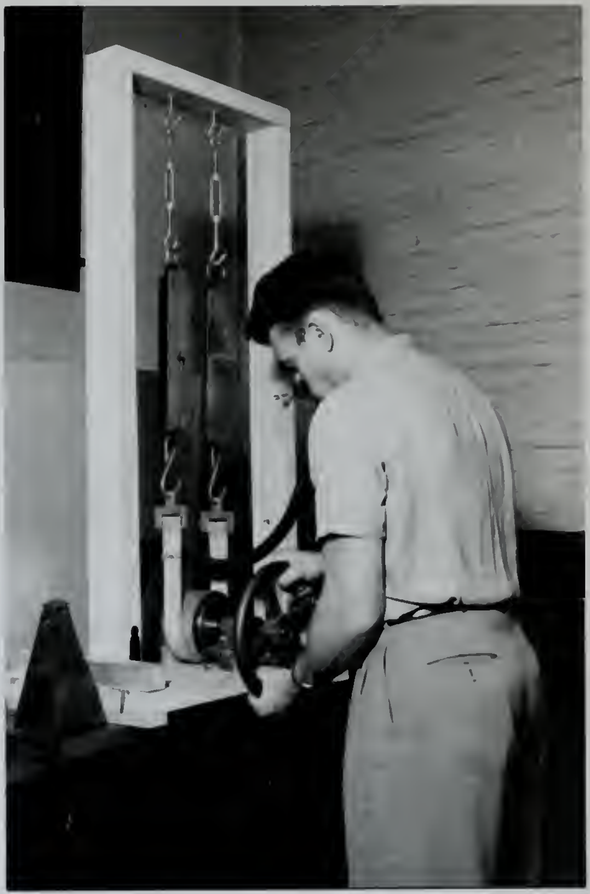

Figure 2

Operator Performing Task

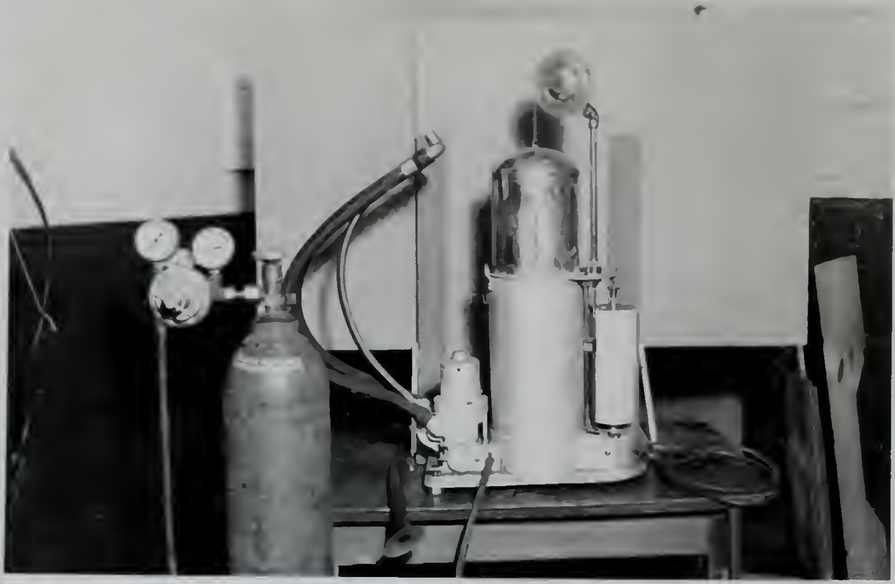

Figure 3

Sanborn EIS Metabolism Tester

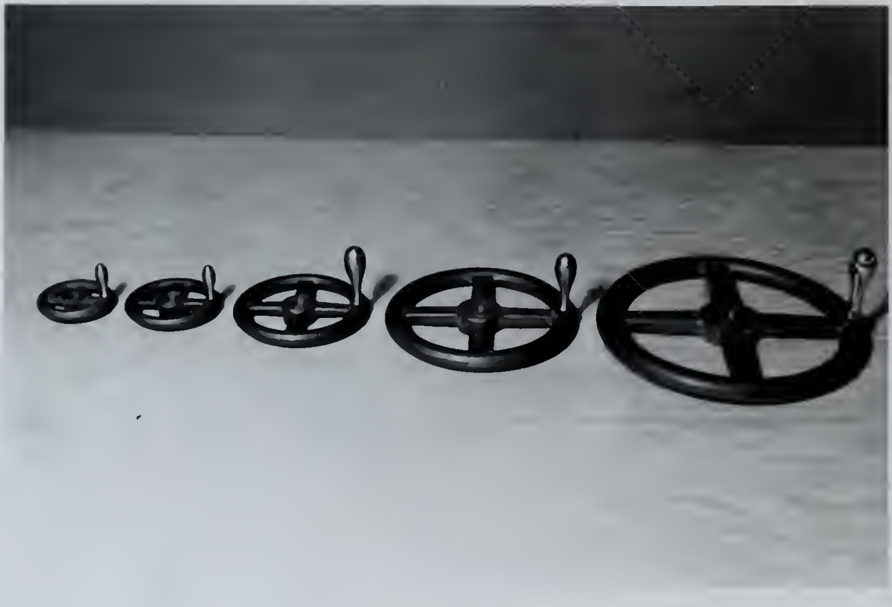

Figure 4

Set of Handwheels

RESULTS

Tables 6 to 10 contain a summary of the data obtained. In these tables the rate of oxygen consumption is expressed as the slope of the line of least squares fitted to the raw data appearing in the wax charts. The raw data upon the wax charts appear as a number of almost vertical lines representing the subjects' inhalations and exhalations. The peak points give an indication of the amount of oxygen not yet consumed by the subject. Therefore, the rate at which oxygen is consumed is given by the straight line fitting these peak points. All points appearing during the two-minute testing interval were used to fit the line of least squares. A sample chart and a sample calculation of the slope are contained in the Appendix.

The raw data for this experiment have been filed in the Purdue Motion and Time Study Laboratory. A presentation of the overall mean slopes for each experimental condition appears in Table 12. The 95% confidence interval of these means is shown in the adjoining column of this table.

Assuming that these data followed the normal distribution with homogeneous variances, analyses of variance were made.

The slope values corresponding to each individual torque were analyzed and a summary of results appears at the bottom of the corresponding table.

For torque 10 inch-pounds, Table 6:

(a) The subjects' means were significantly different at the 1% level.

(b) The handwheel means were not significantly different.

For torque 15 inch-pounds, Table 7:

(a) The subjects' means were significantly different at the 1% level.

(b) The handwheels' means were significantly different at the 1% level.

For torque 30 inch-pounds, Table 8:

(a) The subjects' means were significantly different at the 1% level.

(b) The handwheels' means were significantly different at the 1% level.

For torque 45 inch-pounds, Table 9:

(a) The subjects' means were significantly different at the 1% level.

(b) The handwheels' means were significantly different at the 1% level.

For torque 60 inch-pounds, Table 10:

(a) The operators' means were not significantly different.

(b) The handwheels' means were significantly different at the 1% level.

The analysis of the data as a whole gave the following results (Table 11):

(a) The handwheels' means were significantly different at the 1% level.

(b) The differences between the torque means were very significant.

(c) The operators' means were not significantly different.

(d) The interaction between handwheels and torques was significant at the 1% level.

(e) The interactions between handwheels and operators, and torques and operators, were significant at the 5% level.

A plot of the observed mean slopes versus the diameters of the handwheel is shown in Figure 5.

Table 6

SUMMARY OF SLOPES

Torque 10 Inch-Pounds

Operator Handwheel	1	2	3	4	5	6	7
4"	.397	.614	.485	.378	.338	.393	.380
5"	.515	.575	.408	.408	.336	.484	.429
7"	.477	.554	.344	.476	.395	.470	.483
10"	.532	.584	.487	.343	.412	.393	.375
14"	.518	.586	.505	.334	.536	.566	.461

All slopes are negative.

ANALYSIS OF VARIANCE

	Sum of Squares	df	Mean Square	F	F Required[10] 5% Level	 1% Level
Operators	.121084	6	.020177	6.71	2.51	3.67
Handwheels	.026096	4	.006524	2.17	2.78	4.22
Operators x Handwheels	.072120	24	.003005			

Values from tables in: 10. Snedecor, G. W., *Statistical Methods*, Iowa State College Press, Ames, Iowa, 1946, pp. 222-225.

Table 7

SUMMARY OF SLOPES

Torque 15 Inch-Pounds

Operator	1	2	3	4	5	6	7
Handwheel							
4"	.585	.869	.732	.527	.501	.790	.576
5"	.523	.547	.405	.411	.403	.643	.405
7"	.441	.500	.477	.356	.395	.576	.375
10"	.500	.542	.534	.432	.505	.595	.536
14"	.533	.620	.475	.403	.409	.644	.558

All Slopes are Negative.

ANALYSIS OF VARIANCE

	Sum of Squares	df	Mean Square	F	F Required[11] 5% Level	F Required[11] 1% Level
Operators	.209503	6	.034917	11.23	2.51	3.67
Handwheels	.177078	4	.044270	14.24	2.78	4.22
Operators x Handwheels	.074635	24	.031097			

[11] From: Snedecor, G. W., (Op. Cit.).

Table 8

SUMMARY OF SLOPES

Torque 30 Inch-Pounds

Operator	1	2	3	4	5	6	7
Handwheel							
4"	.848	.919	.896	.774	1.006	.819	.707
5"	.622	.872	.614	.594	.646	.643	.619
7"	.629	.710	.598	.543	.594	.659	.558
10"	.525	.743	.612	.485	.583	.551	.613
14"	.669	.687	.749	.457	.569	.666	.621

All slopes are negative.

ANALYSIS OF VARIANCE

	Sum of Squares	df	Mean Square	F	F Required[12] 5% Level	 1% Level
Operators	.131579	6	.021930	5.41	2.51	3.67
Handwheels	.315573	4	.078893	19.47	2.78	4.22
Operators x Handwheels	.097221	24	.004051			

---

[12] From: Snedecor, G. W., (Op. Cit.).

Table 9

SUMMARY OF SLOPES

Torque 45 Inch-Pounds

Operator Handwheel	1	2	3	4	5	6	7
4"	1.052	1.064	.926	.867	1.198	1.038	.714
5"	1.049	.961	.755	.867	1.190	.728	.778
7"	.678	.843	.722	.556	.770	.895	.642
10"	.715	.764	.690	.594	.710	.765	.534
14"	.648	.760	.692	.564	.653	.818	.552

ANALYSIS OF VARIANCE

					F Required[13]	
	Sum of Squares	df	Mean Square	F	5% Level	1% Level
Operators	.291069	6	.048512	5.32	2.51	3.67
Handwheels	.552243	4	.138061	15.13	2.78	4.22
Operators x Handwheels	.219025	24	.009126			

[13] From: Snedecor, G. W., (Op. Cit.).

Table 10

SUMMARY OF SLOPES

Torque 60 Inch-Pounds

Operator Handwheel	1	2	3	4	5	6	7
4"	1.365	1.139	1.495	1.478	1.871	1.498	1.068
5"	1.311	1.125	1.059	.906	.923	1.583	.924
7"	.596	.828	.787	.664	.835	1.008	.825
10"	.692	.877	.717	.718	.857	.670	.578
14"	.704	.877	.955	.585	.611	.704	.681

All slopes are negative.

ANALYSIS OF VARIANCE

	Sum of Squares	df	Mean Square	F	F Required[14] 5% Level	F Required[14] 1% Level
Operators	.264145	6	.044024	1.36	2.51	3.67
Handwheels	2.482145	4	.620536	19.12	2.78	4.22
Operators x Handwheels	.778721	24	.032447			

---

[14] From: Snedecor, G. W., (Op. Cit.).

Table 11

ANALYSIS OF VARIANCE

Source	Sum of Squares	df	Mean Square	F	F Required[15] 5%	1%
Handwheels	1.838418	4	.459604 (i)	F_1=20.63	2.78	4.22
Torques	5.908240	4	1.477060 (ii)	F_2=59.78	2.78	4.22
Operators	.424332	6	.070722 (iii)	F_3= 1.79	2.14	2.90
Handwheels x torques	1.714752	16	.107172 (iv)	F_4= 7.92	1.75	2.19
Handwheels x operators	.534754	24	.022281 (v)	F_5= 1.64	1.63	1.98
Torques x operators	.593028	24	.024710 (vi)	F_6= 1.82	1.63	1.98
Handwheels x torques x operators	1.299979	96	.013541 (vii)			

$F_1 = \frac{(i)}{(v)}$ $F_2 = \frac{(ii)}{(vi)}$ $F_3 = \frac{(iii) + (vii)^{*}}{(v) + (vi)^{**}}$ $F_4 = \frac{(iv)}{(vii)}$ $F_5 = \frac{(v)}{(vii)}$ $F_6 = \frac{(vi)}{(vii)}$

$$\text{*Num. df.} = \frac{\left[(iii) + (vii)\right]^2}{\frac{(iii)^2}{6} + \frac{(vii)^2}{96}} = 8.5$$

$$\text{**Den. df.} = \frac{\left[(v) + (vi)\right]^2}{\frac{(v)^2}{24} + \frac{(vi)^2}{24}} = 48$$

[15] From: Snedecor, G. W., (Op. Cit.).

Table 12

MEAN SLOPES

Torque 10 Inch-Pounds

Handwheel	Mean Slope	95% Confidence Interval
4"	.426	.339-.513
5"	.448	.375-.521
7"	.457	.394-.520
10"	.446	.363-.529
14"	.508	.445-.571

Torque 15 Inch-Pounds

Handwheel	Mean Slope	95% Confidence Interval
4"	.654	.422-.786
5"	.477	.387-.567
7"	.446	.374-.518
10"	.520	.474-.566
14"	.520	.433-.607

Torque 30 Inch-Pounds

Handwheel	Mean Slope	95% Confidence Interval
4"	.853	.762-.944
5"	.658	.570-.748
7"	.613	.559-.667
10"	.587	.510-.664
14"	.631	.543-.712

Table 12 (cont.)

MEAN SLOPE

Torque 45 Inch-Pounds

Handwheel	Mean Slope	95% Confidence Interval
4"	.980	.834-1.126
5"	.904	.745-1.063
7"	.729	.621-.837
10"	.682	.602-.760
14"	.670	.580-.760
	Torque 60 Inch-Pounds	
4"	1.416	1.170-1.662
5"	1.119	.887-1.351
7"	.835	.738-.932
10"	.730	.633-.827
14"	.730	.605-.855

$$s_x = \sqrt{\frac{\sum x^2 - \frac{(\sum x)^2}{7}}{6}}$$

$$t_{.05} = 2.45$$

$$\text{95\% of confidence in true mean} = \text{observed mean} \pm 2.45 \frac{s_x}{\sqrt{7}}$$

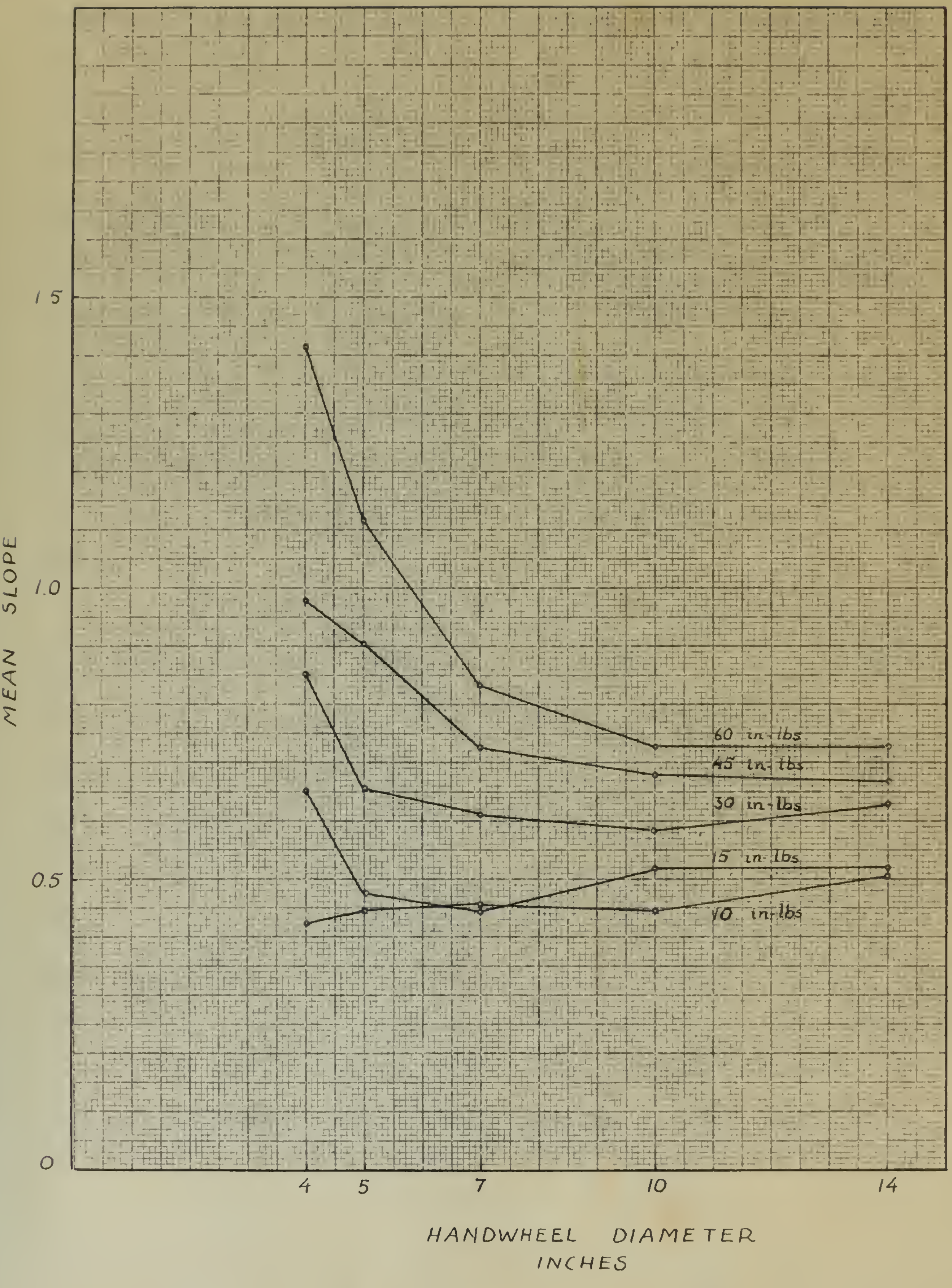
MEAN SLOPE
1.5
1.0
0.5
0
4
5
7
10
14
HANDWHEEL DIAMETER
INCHES
60 in-lbs
45 in-lbs
30 in-lbs
15 in-lbs
10 in-lbs

Fig. 5

DISCUSSION OF RESULTS

The previous work with this equipment involved, always, low levels of gaseous exchanges; therefore, its use at relatively high levels, as was the case of most conditions of the present investigation, might be questionable. One objection might be the possible limitations in the capacity of the carbon dioxide absorber (Metabolime). This condition would cause errors that would increase with increasing oxygen consumption rate. Nevertheless, the testing conditions were such as to require substantial differences of oxygen consumption; hence, even in the presence of errors in the absolute values of the rates, the trend of variation of these rates is fairly well defined.

Unreliable data would also result from testing situations demanding muscular over-exertion. It is a well known fact that a hard-working muscle will require more oxygen than can be brought to it by the blood stream. However, it keeps on working in a fatigue condition and incurs what is called an oxygen debt. The occurrence of this extreme condition would invalidate the basic assumption of proportionality between the effort output and the oxygen consumption. This would show up in a tendency of the section of the plot corresponding to high torques and small handwheels to stay below a certain maximum slope with the

resulting confusion of the lines corresponding to the various torques. The spreading of the graph lines for increasing torques and decreasing sizes seems to be a good indication that the levels of effort tested were well below the ones that would cause oxygen debts.

It was the intention of the experimenter to use the basal rates, taken for each session, as a reference level for the task rates of the same session, thus, partially, eliminating possible variations due to fluctuations of subject's physical conditions. This basal rate was obtained recording the subject's oxygen consumption while he was in a standing position, without motion of any body member. The original idea was to find the difference between rates corresponding to the two conditions: (1) standing motionless, and (2) standing performing the task. It was noticed, however, with some operators, that the motionless condition was such as to cause irregularities in the basal breathing rate. It seemed that in the absence of something else to concentrate upon, these operators became what can be called breathing-conscious, and tried to control their inhalations and exhalations. Complaints about the difficulty in breathing pure oxygen followed these runs. It must be said that these difficulties disappeared in the case of task-runs. In order to distract these operators, and minimize this effect, they were told to follow mentally the metronome beats, by counting or otherwise. This

resulted in somewhat smoother charts.

Another difficulty was the easily detectable increase in the slope that appeared in some basal runs. These increases were accentuated after the first two minutes of the recording period. The occurrence of these increases might be explained by an increasing demand of oxygen due to the standing attitude alone. As an attempt to overcome this difficulty, the basal slopes were computed using only the two first recorded minutes.

As a third consideration, the comparison of the basal slopes with the ones corresponding to the low-torque runs showed very small differences, perhaps smaller than the error inherent in the equipment.

Due to the above reasons, the basal rates were abandoned as a whole, and the task slopes were used with no further consideration of reference levels. The lack of significant differences among operators, as shown by over-all analysis of variance, may serve as an additional justification for this action.

The data were not corrected for atmospheric pressure and temperature, the effects of these factors being negligible.

CONCLUSIONS

It may be concluded from the data obtained in this experiment that to overcome torques in the range investigated, using the method specified, and with operator energy expenditure as the criterion, the largerhandwheels are more effective.

Inspection of the torque graphs (Figure 5) indicates that for the torque range between 30 and 60 inch-pounds little is gained by going beyond the 10 inch diameter.

For torques in excess of 45 in pounds, handwheels of smaller diameter than seven inches are undesirable, and for torques below that level the minimum limit can be taken as 5 inches.

For a torque of 15 inch-pounds, the existence of a minimum indicates that the optimum handwheel diameter is in the neighborhood of 7 inches. For the 30 inch-pounds torque, a not-so-striking minimum can be noticed at the point corresponding to the 10 inches handwheel.

Even though the statistical analysis of the data corresponding to the 10 inch-pounds torque shows no significant differences, a glance at the plot indicates a slight tendency of the slope to increase with the diameter; and, one might advance the conclusion that to overcome very low torques small handwheels should be chosen.

What has been referred to as the secondary purpose should be real value to other experimenters using the same equipment.

The results obtained in this experiment indicate that the Sanborn EIS Metabolism Tester can be accepted as a device for measuring human energy at reasonably high output levels.

The foregoing conclusions are in general agreement with the findings of Fichman[16], who performed a similar experiment.

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[16] Fichman, H. T., "The Effect of Diameter on the Effort Required to Rotate Handwheels Used as Cranks", Unpublished Master of Science Thesis, Purdue University, Lafayette, Indiana, 1952.

APPENDIX

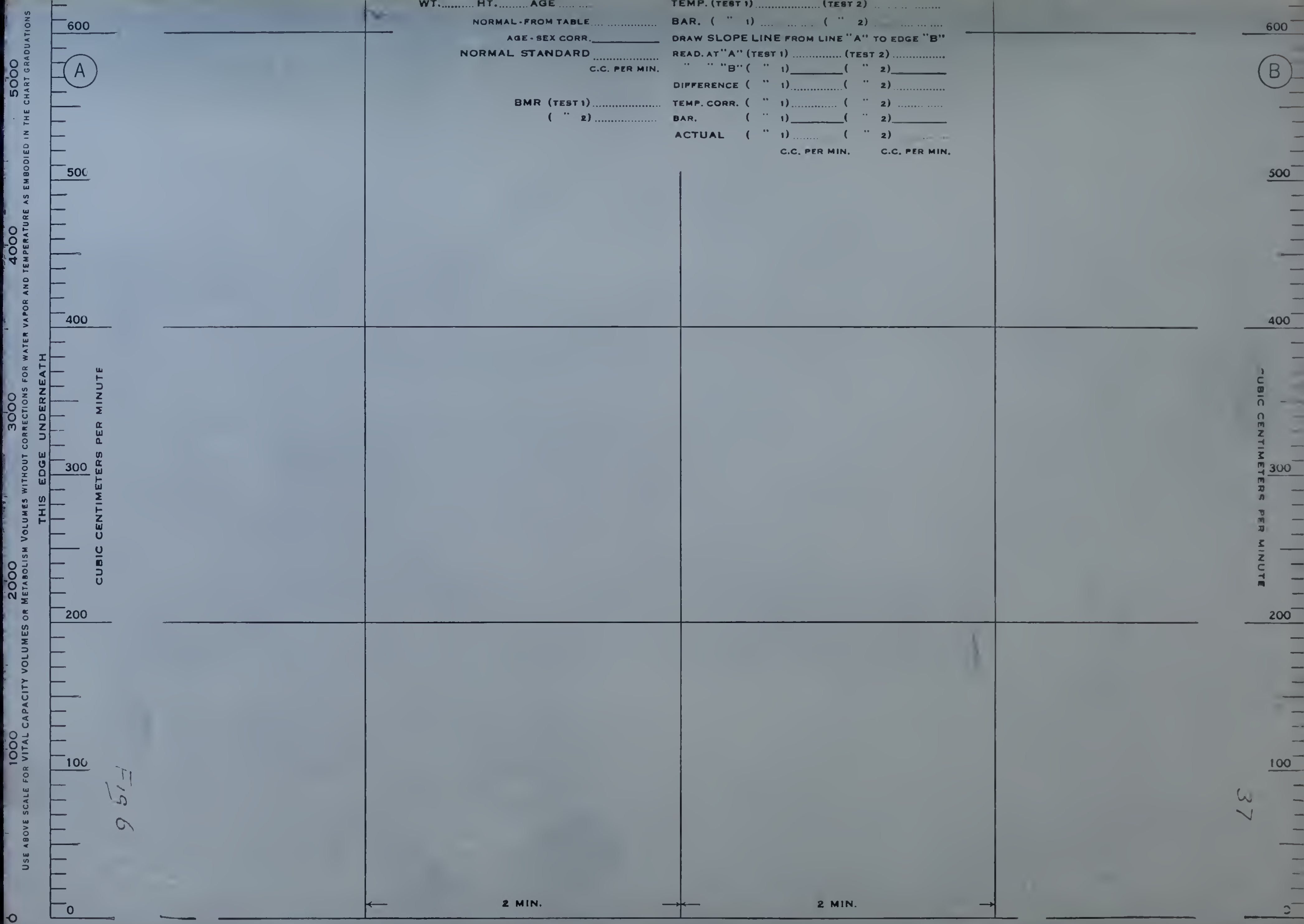

Fig 6

WT.......... HT.......... AGE ....
NORMAL - FROM TABLE ....
AGE - SEX CORR. ____________
NORMAL STANDARD ....
C.C. PER MIN.

BMR (TEST 1) ....
(" 2) ....

TEMP. (TEST 1) .... (TEST 2) ....
BAR. (" 1) .... (" 2) ....
DRAW SLOPE LINE FROM LINE "A" TO EDGE "B"
READ. AT "A" (TEST 1) .... (TEST 2) ....
" " "B" (" 1) ________ (" 2) ________
DIFFERENCE (" 1) .... (" 2) ....
TEMP. CORR. (" 1) .... (" 2) ....
BAR. (" 1) ________ (" 2) ________
ACTUAL (" 1) .... (" 2) ....
C.C. PER MIN. C.C. PER MIN.

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SLOPE CALCULATION

Chart No. ________ Run No. ________ Operator ____________________________

CHART VALUES

X	Y	X	Y

CALCULATED VALUES

EX ____________ 2EXY __________

EY ____________ EX^2 __________

EXY ____________________

NEXY ____________________

EXEY ____________________

$(EX)^2$ ____________________

NEX^2 ____________________

$$b = \frac{EXEY - NEXY}{(EX)^2 - NEX^2}$$

Fig. 7

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

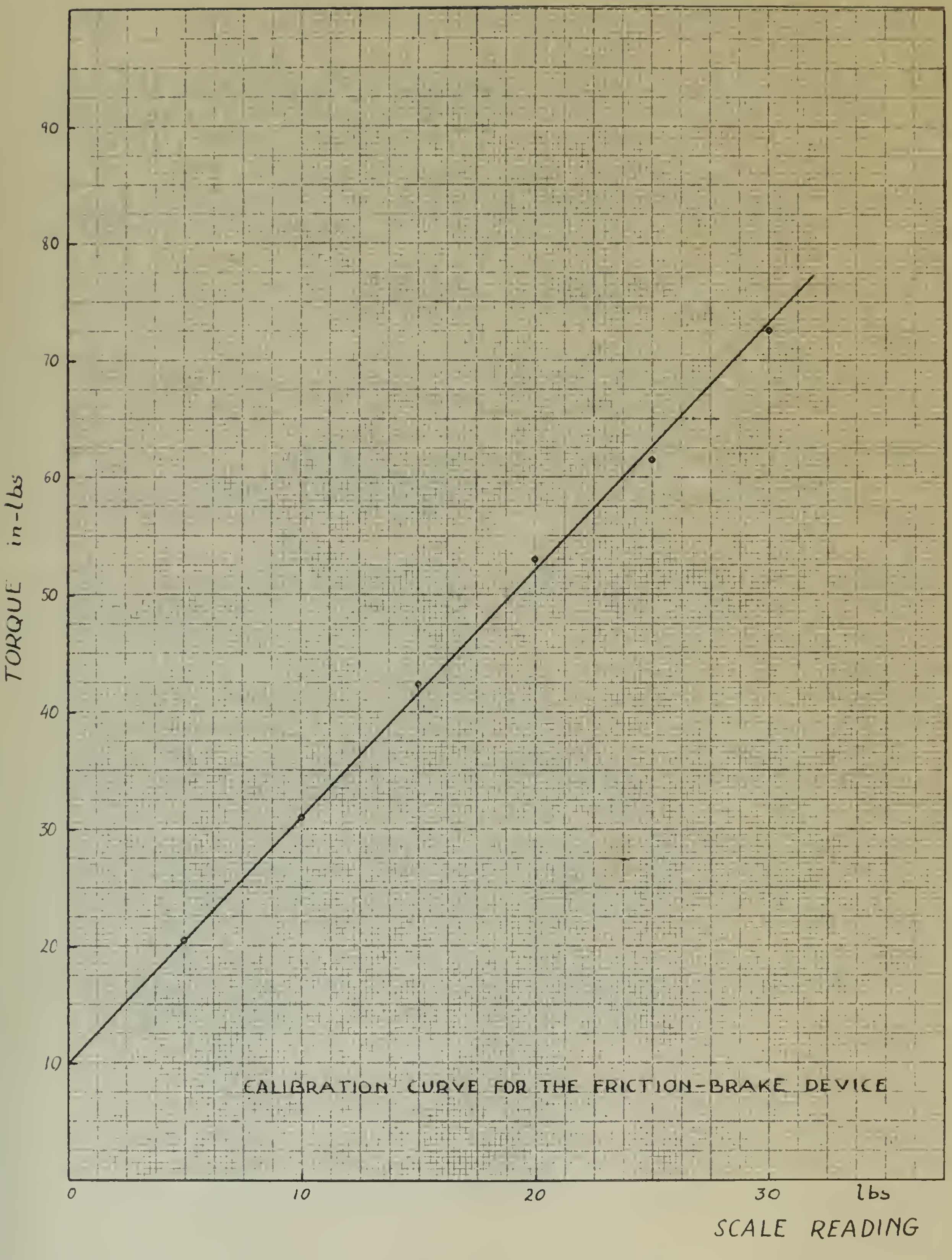
TORQUE in-lbs
90
80
70
60
50
40
30
20
10
0
10
20
30
lbs
SCALE READING
CALIBRATION CURVE FOR THE FRICTION-BRAKE DEVICE

Fig. 8

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